DIE CASTING RESEARCH

Annual Progress Report for Period
June 29, 1994 - June 30, 1995

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Annual Report

on

**Evaluation of Chromium Carbide and Other CVD
Coatings to Improve the Wear Resistance of
Aluminum and Zinc Die Casting Dies**

Submitted to

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This 18-month project started on January 15 of 1995. The following objectives were accomplished during the first two quarters of research efforts.

- i). Continuation of erosion, corrosion and cyclic oxidation testing of OSU chromium carbide coating on H13 pins. The test results will guide our industrial coating partner in selecting their promising coating for the application in H13 die steels.
- ii). Project review meeting on March 22 in Cleveland, Ohio. A industrial monitor team, lead by Peter Ried of Doehler-Jarvis was formed. A tentative project plan and schedule was passed in this meeting. A list of potential cooperation industrial partnership was issued. It was decided that Balzers Tool Coating Inc. and a die casting company with multi-cavity die will join the Ohio State University in this research project. This project requires significant contribution for industries in term of coating suppliers and casting campaign.
- iii). Meeting with Industrial die casting partner: General Die Casters in Cleveland, Ohio. Several issues were discussed such as identification of multicavity die in the shop floor, the casting alloy 380, the process conditions and the key measurement of wear behavior of die materials and coatings.
- iv). Feasibility study of available potential commercial coatings in this project. A plant visit and cooperative discussion with the engineering group of Balzers Tool Coating Inc. was arranged on May 12. Several important coating issues were resolved: the die substrate hardness, the type of PVD and CVD coating to be tested, the die maintenance schedule, the frequency of off-line measurement, etc.
- v). A "State of Art" literature review was completed. The review paper "Application of Commercial Coating in Aluminum Die Casting" will be published in the International Conference on Advanced Technologies in Die/Mold Manufacturing to be held on October 10-12 in Columbus, Ohio.
- vi). A Survey on Use of Die Coatings in Die Casting Industry was distributed through NADCA local chapters. The compilation of the review will be distributed to our NADCA members for their references. This review will benefit our selection of die coating in this project.
- vii). Coating Task Group Report was made during the NADCA Die Materials Committee on Wednesday, June 21, 1995. Prof. Rajiv Shivpuri presented the recent progress on the die materials and coating research at the Ohio State University. Due to the arising difficult to contribute its four cavity die for testing, Ganton Technologies was mentioned for contact as a research partner in this project. A joint meeting with Ganton is under consideration.

Annual Report

o n

**Die Cavity Instrumentation
OSURF Project 729390**

Submitted to

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Annual Report
Die Cavity Instrumentation Project
OSURF Project 729390
Department of Energy DE-FC07-941D13223
Report Period: July 1, 1994 - June 30, 1995

Introduction and Background

Project Structure and Participants

This is the first annual summary report prepared by the OSU Center for Die Casting and submitted to the Department of Energy (DOE) for the project entitled "Die Cavity Instrumentation". The mission of this two year duration study is to evaluate and develop thermal, pressure, and gas flow rate sensors to monitor filling, solidification, and gas entrapment in the die cavity(s) of cold chamber die casting machines and to relate the measurements of those variables to the quality of the resultant die castings. The successful completion of this project should allow die casting engineers additional and improved sensors with which to monitor and control both the die casting process and the resultant products. The report period covered is the twelve month period from July 1, 1994 through June 30, 1995.

The project is also supported and monitored by The North American Die Casting Association (NADCA), and the Ohio State University Engineering Research Center for Net Shape Manufacturing (ERC/NSM). The principal researchers on this project are Professor Carroll Mobley of the Department of Materials Science and Engineering, and Professor Jerry Brevick of the Industrial, Welding, and Systems Engineering Department. Graduate Research Associates Patrick Cheng, Vasanth Venkatasamy, and Nao Tsumagari were funded by and worked on the project.

This project is both assisted and monitored by the North American Die Casting Association (NADCA) Process Technology Task Group, chaired by Mr. Gary Pribyl of Heick Die Casting Corporation. Current membership and company affiliation of the NADCA Process Technology Task Group is given in Appendix A. Dates and places of project review meetings held during this report period are listed in Appendix B.

Technical Background of Project

Die casting is a near net shape manufacturing method in which molten metal is injected at high velocities into reusable metallic molds and solidified with pressure applied to the casting. The fluid velocity as it enters the casting cavity generally exceeds 20 m/s, which produces atomized flow during the initial stage of cavity filling. Die casting is one of the most cost effective near net shape manufacturing processes for mass production of thin walled, complex shape products. It is the most commonly used casting process for aluminum, zinc, and magnesium alloy castings. Die casting provides the best surface finish and highest commonly achievable dimensional tolerance among any other casting methods. This technique allows production of a wide variety of shape and size castings. Aluminum alloy die castings vary in weight from a few grams to 20 kilograms. Die castings include complex shape products such automotive engine blocks and transmission cases. Various casting processes for aluminum alloys are compared in Table 1[1].

Table 1. Comparison of Casting Processes for Aluminum Alloy[1].

	Sand Casting	P/M Casting	Die Casting
Minimum Wall Thickness, mm	3.0-5.0	3.0-5.0	1.0-2.5
Common Linear Tolerance, mm/m	300	10	4
Surface Finish, μm	6.5-12.5	4.0-10	1.5
Cooling Rate, $^{\circ}\text{C/s}$	0.1-0.5	0.3-1.0	50-500

* P/M = Permanent Mold

Cooling Rate is highest value achieved.

Aluminum alloy die castings are traditionally made using the cold chamber die casting process. A schematic of a cold chamber die casting machine is shown in Figure 1. Unlike zinc and some magnesium die casting process, aluminum alloy is melted in a furnace separated from the melt injection system. The molten metal is transported from the melting or holding furnace, introduced into a shot sleeve, and then injected into the die cavity. A cold chamber die casting machine usually consists of a melting furnace, ladling system, molten metal injection system, die holding system which utilizes part ejection capability, and spraying system. The variables which must be controlled to reproducibly make acceptable quality parts are listed in Table 2. The system components and operating variables are described by Sully[2], and Kaye and Street[3]. Product specification standards for die castings are available from the North American Die Casting Association (NADCA) [4].

Figure 1. Schematic of die casting machine^[5]

Process variables which must be controlled in all die casting campaigns are listed in Table 2. The listed variables are determined prior to a campaign and maintained constant throughout the production period. Cycle times vary from 15 seconds for a small part to 2 minutes (120 seconds) for a larger part, such as a transmission housing. Machines are usually operated on a near continuous basis. Kaye and Street⁽³⁾ and Herman^[6] describe the state-of-the-art for instrumentation of the cold chamber die casting systems.

Table 2: Casting Variables for Cold Chamber Die Casting

Melting Furnace	Alloy Composition Melt Temperature Melt Treatment
Ladling System	Ladling Time
Metal Injection System	Shot Sleeve Dimensions Shot Delay Time Shop Profile Cavity Fill Time Intensification Pressure
Dies	Tie Bar Load Part Configuration Parting Line Design Runner Design Ingate Location and Size Cooling Line Location Venting Method Vent Location Die Temperature
Ejection System	Die Open Time Ejection Timing Ejector Pin Location
Spraying	Spray Type Spraying Timing Spraying Duration Spraying Amount

The die casting variables are sometimes determined during part design and final properties are predicted before a die is machined. This is extremely important in die casting because dies are the most expensive component in the die casting process. Once dies are machined, it is difficult, time consuming, and costly to change them.

A methodology for controlling properties of net shape manufacturing is described in Figure 2. Casting variables are the only variables that can be changed during casting operation. A simple listing of the die casting operating conditions is not sufficient to predict casting properties. Casting properties are directly related to casting microstructures. A few variables are generally adequate to predict the casting microstructures. Those are the solidification conditions, which consist of the temperature gradient at the liquid-solid interface, the solidification rate, the cooling rate, the flow velocity of liquid in the liquid-solid "mushy" zone, and the number or density of nucleation sites in the liquid. These solidification conditions are usually calculated from given casting operational variables using solidification analysis software. Microstructures predicted using a computer simulation program were in good agreement with actual microstructures in aluminum-silicon alloy sand castings [7]. The high fluid flow velocity experienced in the die casting process makes the simulation of die casting solidification conditions difficult. The ability to predict die casting microstructures, even using a computer simulation, is limited today.

A reasonable premise is that die castings made under controlled and reproducible operational conditions will have reproducible die casting structures and properties. Reproducibility of die cast parts is one of the biggest issues in the die casting industry. Despite reasonable control on the operational variables, defective parts are sometimes made. In a previous study of reproducibility of die cast parts, Naizer measured the volume percent of porosity (% Porosity) in various types of commercial aluminum alloy die castings made sequentially under stable and controlled die casting conditions [8]. Figures 3 and 4 are some of his results for % Porosity for sequentially die cast parts. The % Porosity variation obtained from ten sequentially made die castings in Figure 3 implies that there was a large shot-to-shot variation during the die casting operation. The supplier of this set had some unknown casting variables which were changing and strongly influencing the formation of porosity. Figure 4 indicates that the supplier of this particular set of castings had a controlled die casting operation, and the % Porosity values were more reproducible. The die casting operational variables which both suppliers used were not given to Naizer, so it was not known what conditions caused these differences.

Figure 2. Diagram of property control in casting processes^[7]

Figure 3. Archimedes' percent porosity values for sequential, quasi-steady state Group I die castings[8]

Figure 4. Archimedes' percent porosity values for sequential, quasi-steady state Group III die castings[8]

Most of the process control parameters and variables listed in Table 2 are measured away from the die cavity. Measurement of the thermal and pressure fields in the casting and die near the casting-die interface is expected to provide the most sensitive records of the conditions under which the part is manufactured. This project is focused on evaluating process monitoring sensors which record the thermal, pressure, and gas flow rates in or near the die cavity as a means of securing improved process sensors whose outputs correlate better with resultant part quality.

Data for the plunger tip position and hydraulic pressure as a function of time during filling of the shot sleeve, runner(s), and die cavity are commonly measured on state-of-the-art die casting systems. A representative plot of plunger position and hydraulic pressure as functions of time are shown in Figure 5.

Figure 5. Plunger position and hydraulic pressure history chart^[3]

The following variables are commonly obtained from the position and pressure records and used to monitor the die casting process and part quality. Those variables are;

- Average fast shot velocity
- Average slow shot velocity
- Fast shot position
- Total shot length
- Final shot pressure
- Intensifier rise time
- Fill time
- Peak fast shot velocity
- Travel past impact

and

How the die casting qualities, defined by such measurables as total porosity, porosity distribution, and surface finish, depend on each of the operational variables is not thoroughly known.

In preparation for the use of the die cavity sensors evaluated as part of this project, a ShotScope plunger position and velocity recording system was installed on the OSU ERC/NSM Buhler 250h die casting system. A improved version of the Buhler die casting system (the Buhler SC) system is to be installed in the OSU ERC/NSM manufacturing laboratory during mid-August, 1995. The Buhler SC machine has an improved shot control system, which will significantly improve the ability to collect plunger position-time data with which to interpret the die cavity filling and solidification phenomena. The temperature and pressure versus time records to be taken from the die cavity sensors evaluated in this project will be synchronized with the plunger position-time record, obtained from the ShotScope recording system, and the cylinder hydraulic pressure-time record taken directly from the Buhler die casting machine.

Project Tasks

The project consists of seven subtasks identified below:

- Subtask 1: Identify and contact commercial suppliers of die casting and related sensors and monitoring systems and obtain descriptions and costs of candidate units.
- Subtask 2: Procure and install selected sensors identified during Subtask 1 on the OSU ERC/NSM die casting system. Evaluate the sensors through die casting trials.
- Subtask 3: Correlate sensor data with traditional operating data. Predict and measure gate freezing times and cavity pressure in relation to machine hydraulic pressure record.
- Subtask 4: Characterize die castings for porosity and contained gas contents and relate to Subtask 3 activities.
- Subtask 5: Identify several commercial die casting facilities to perform in-plant evaluations of sensors and methodologies developed during first year of project.
- Subtask 6: Participating die casting facilities install and evaluate cavity sensors during controlled production campaigns.
- Subtask 7: Characterize porosity and contained gas contents of die castings produced during beta site campaigns and develop correlations between product quality and sensor responses.

The sensors to be evaluated in this project should allow the measurement of (a) the die temperature field near the die cavity surface, (b) the pressure of the liquid in the die cavity, and (c) the amount of gas exiting the die cavity during filling. These measurements are to be correlated with the plunger position-time and the hydraulic pressure-time records, and related to the porosity of the resulting parts. A schematic of the sensor locations and functions is shown in Figure 6.

Figure 6: Schematic of Location and Function

Literature Survey

The technical literature relating to the cold chamber die casting process was reviewed to identify papers pertaining to temperature, pressure, and gas flow rate sensors. Seventeen references pertaining to sensors and procedures for monitoring the conditions of the die cavity were found and are listed in Appendix C. 14 of the 17 references are contained in NADCA publications.

Survey of Die Cavity Sensor Usage

To obtain an assessment of the current usage of sensors to measure the thermal and pressure fields and gas flow rates from the die cavity, a survey questionnaire was prepared and submitted to a number of US. die casting companies. The questionnaire of die cavity instrumentation is included as Appendix D. The questionnaire was sent to NADCA corporate members and also distributed to company representatives attending NADCA Chapter meetings. The completed questionnaires were returned to the Ohio State project investigators and the responses were tabulated. 63 completed surveys were returned to OSU. 60 of the responses were completed by US. die casters companies. 1 survey was completed by a foreign (non-North American) die casting company. 2 surveys were completed by US. die casting equipment manufactures. The responding die casting companies operate 937 cold chamber machines and 343 hot chamber machines. The total of 1249 die casting machines included by the responding U. S. die casting companies represent 15.6% of the available US. die casting machines, based on the estimated 8000 die casting machines in 1994.

91% of the responding companies indicated that they possess the equipment to monitor the position and velocity of the plunger as a function of time during the filling process. 50% of the responding companies indicated that they have used temperature and pressure measuring sensors near the die cavity as part of the process monitoring or control practices. Only 15% of the responding companies indicated that they use or have available systems to monitor the extend to which the vents are open or functioning. Only 12% of the responding companies indicated that they use or have available systems for measuring the amount of gas which is removed from the die cavity during filling. The OSU investigators surmised that the companies indicating that they monitored the amount of gas removed from the die cavity used die cavity vacuum assisted practices.

Based on the results of the die cavity instrumentation survey, the evaluation of sensors to monitor the amount of gas exiting the die cavity to the atmosphere during filling was selected as a priority. The evaluation of the robustness and significance of near cavity temperature sensors and liquid pressure sensors was considered important by the OSU investigators and the members of the NADCA Process Technology Task Group.

Near Die Cavity Sensors

In the 1988 SDCE publication Die Casting Process, Engineering & Control, Herman^[6] provides a listing of instrumentation manufacturers, many of whom provide sensors which could be used to monitor the thermal fields in the vicinity of the die cavity and the pressure of the liquid in the die cavity. No manufacturer of sensors to monitor the amount of gas exiting the die cavity through the vents is given as part of Herman's instrumentation manufacturers listing.

Near Cavity Temperature Sensors

One of the objectives of this study is to experimentally determine the thermal fields in the die near the casting cavity to (1) monitor the reproducibility of the thermal conditions of the process, (2) determine the heat flux and total heat removed from a region of the die and casting, (3) determine the freezing times of the gate(s) and regions of the casting. The experimental determination of the thermal fields in die can also be used to gauge the adequacy of analytical and/or numerical heat transfer models for the die casting process.

Prior work^[9] using a thermal probe consisting of three or more thermocouples in a linear array relative to the die cavity interface has shown that such a probe allows adequate characterization of the die thermal field near the die cavity to meet the thermal field measurement requirements of this project. A representative temperature versus time record from a multiple thermocouple probe for a 380 aluminum alloy part cast in a H-13 steel die is shown in Figure 7.

The characteristic temperatures used to define the reproducibility of a particular die casting practice include:

- a. the initial die surface temperature, T_{initial} ,
- b. the maximum die surface temperature, T_{max} ,
- c. the die surface temperature at the time when the die is opened,
 T_{open} ,

and

- d. the minimum die surface temperature, T_{min} ,

Figure 7. Representative Thermal Probe Response^[9]

In addition, since the probe contains multiple thermocouples located at known distances from the cavity-die interface, the thermal gradient, dT/dx , at the interface can be calculated and used to determine the heat flux delivered to the die as a function of time. Based on the thermal gradient data from the probe, the reproducibility of the die casting conditions is also judged by:

- a. G_{max} , the thermal gradient about the die interface at the time when the die surface temperature reaches its maximum value, T_{max} .
- b. G_{min} , the thermal gradient about the die interface at the time when the die surface reaches its minimum value, T_{min} .
- c. Q , the total heat delivered to the die during the process.

A representative plot of the die surface temperature, heat flux, and total heat delivered to the die during the die closed period of a die casting cycle for 380 aluminum alloy in a H-13 steel die is shown in Figure 8.

Figure 8. Representative Plot of Die Surface Temperature, Heat Flux and Total Heat Absorbed during a Die Casting Cycle¹⁹¹

The heat flux as a function of time can also provide insight into the reproducibility of the die lubricant spraying practice and the constancy or change in heat transfer coefficient at the casting-die interface. While extremely long term operating data (for example, measurements of die life) are not a part of this study, it is expected that the variations in G_{max} and G_{min} should correlate with die life based on thermal fatigue.

As the die casting process is a cyclic process, the process designer and operator attempt to have the process conducted with quasi-steady state thermal conditions. For preferred operating conditions, the die casting system is brought to the thermal quasi-steady state condition (typically requiring 20 to 50 shots to reach the quasi-steady state thermal condition) and all subsequent parts are cast with identical temperature at specified location versus time records. Since cycle time (the time to produce a given part) frequently varies by 10% in a given die casting campaign, absolute quasi-steady state thermal conditions are not generally achieved. Die casting experiments remain to be conducted to define the allowable ranges in each of the thermal characteristics ($T_{initial}$, T_{max} , T_{open} , T_{min} , G_{max} , G_{min} , and Q) for the production of acceptable quality die castings.

The thermocouple probes designed and used in this project consist of a carrier and an insert made of the same material as the die (H-13 die steel, in this study). The thermocouple probes made in this project are of similar design to

those described in Reference 9. Four type K (chromel-alumel) thermocouples are either capacitor spark discharge welded or silver soldered in holes machined in one of the insert pieces. The tips of the thermocouples are at known locations in the insert, equivalently, at known distances from the die cavity interface. The carrier has the same external dimensions as the pressure probes, to be described in a later section, to allow interchangeability of the thermal and pressure probes in a given die.

The emf versus time data from each of the four thermocouples are recorded using a computer data acquisition system. Computer software is used to calculate the thermal gradients and heat fluxes and plot the temperatures, thermal gradients and heat flux values following a given die casting cycle.

While thermal probes of the type described are appropriate for laboratory studies, it remains to be demonstrated that such probes can be utilized for adequate periods in a manufacturing environment.

Gate Freezing Time

After the cavity is filled, additional pressure is often applied to the metal through the plunger tip. This pressure is called the intensification pressure (See Figure 5). The intensification pressure is generally applied to feed the casting and reduce the porosity in the die castings. The intensification pressure can only effectively feed liquid alloy into the die cavity while the ingate stays liquid. Once the gate is frozen through its thickness, the hydrostatic pressure made by the intensification pressure cannot be transmitted to the casting cavity through the remaining liquid. Thus, the effect of the intensification pressure is lost when the gate completes solidification. Therefore, the gate freezing time is an important variable to monitor and control the soundness of die cast parts.

One of the project goals is to investigate how long the gate remains liquid during a die casting operation, and relate the gate freezing time to the timing of the intensification pressure and the final casting quality. The direct temperature measurement by inserting a thermocouple in a gate is not feasible because any thermocouples inserted in a cavity break after the first shot and any thermocouple located within the small cross sectional areas of the gate would affect the initial flow into the cavity. This project attempts to measure the gate freezing time indirectly by using an array of thermocouples (a thermocouple probe) located at or near the gate of the die. By measuring the thermal gradient in the die at the gate, the freezing time of the gate can be calculated.

A commercial finite difference computer solidification analysis software, MAGMASoft, was used to simulate the gate and part freezing time for a 4 mm thick plate die casting with a 1.5 mm thick wedge gate. An IBM Risc 6000 work

station was used for this simulation. The initial conditions and boundary conditions used in the simulation are listed in Table 3.

Table 3: Simulation Values

Part	Material	Initial Temp., °C
Casting	A380	625
Molds	H13	150
Coolant	Water	50
Heat Transfer Coefficient, W/m ² K		
Casting-Mold		20000
Mold-Coolant		10000
Mold-Mold		1000

Results of the finite difference analysis are influenced by the number of meshed elements. Accuracy increases with increasing number of mesh, but the time required to complete the simulation increases with increasing number of mesh. An appropriate number of elements need to be chosen so that a reasonable simulation result is obtained during a reasonable amount of computing time. The 4 mm thick plate casting geometry, including attached runner, was divided into small elements with three configurations. One consisted of coarse elements, with which the casting had 86270 elements and 5 elements across the gate. The second configuration consisted of medium size elements, with which the casting had 138918 elements and 10 elements across the gate. The last configuration consisted of fine elements, with which the casting had 259453 elements and 18 elements across the gate. The computed gate freezing times (time required to remove the superheat and heat of fusion) for the coarsest and finest elements on the cross-sectional planes obtained at the center of the gate were nearly the same (freezing time were the same within 5%). For all three mesh sizes, the 1.5 mm thick gate completes freezing in about 0.28 s and the 4.0 mm thick part completes freezing after 0.78 s. These results indicate that the gate freezes before the casting, and effective intensification is attainable only for the initial 36% of the total part freezing time. The computer analyses also indicates that the first region to solidify is not precisely at the gate, but slightly (about 1.5 mm) upstream in the runner. These MAGMASoft computer results for gate freezing times do not include any fluid flow effects, which are anticipated to slightly increase the gate freezing times.

The variation of the calculated freezing time along the center of the gate thickness is shown in Figure 9. The horizontal axis in Figure 9 indicates the distance from the gate toward the runner. According to Figure 9, the difference on the freezing time with the number of elements is negligible within the range investigated in this study. 5 elements across the gate were adequate to simulate the gate freezing time.

Figure 9. Solidification Time versus Distance from Gate into the Runner for two mesh sizes.

Cavity Pressure Probes

Two types of pressure sensors are commercially available for measuring the liquid aluminum alloy pressure while in the die cavity. These two type of sensors are (1) load cells/transducers located behind ejector or pressure pins and (2) quartz pressure sensors which are placed direct in contact with the alloy in the die cavity. While a number of companies market load cells/transducers which can be used to monitor the load behind ejector and pressure pins, only one company (Kistler Instrument Corp., Amherst, N.Y.) has been identified which markets pressure sensors which directly contact the alloy in the die cavity. Both types of pressure sensors are available from Kistler Instrument Corp. Buhler SC die casting machines are now equipped with direct cavity quartz pressure sensors. Figures 10 and 11 show the basic geometry, dimensions, and technical data for both type sensors provided by Kistler Instrument Corp.

Technical Data

Range	kN	0 ... 10
Calibrated partial range	kN	0 ... 1
Overload	kN	12
Threshold	N	<0,01
Uniform sensitivity	pC/N	~3,45
Linearity, also for partial ranges	% FSO	≤±1
Hysteresis	% FSO	≤1
Rigidity	N/μm	~160
Natural frequency	kHz	~60
Operating temperature range	°C	-50 ... 200
Temperature coefficient of sensitivity	%/°C	-0,02
Temperature error	N/°C	<±5
Insulation resistance at 20 °C	Ω	≥10 ¹³
at 120 °C	Ω	≥10 ¹²
Weight	g	280

Figure 10. Indirect Pressure Sensor^[10]

The direct pressure sensor is a relatively new product for die casting aluminum alloys. Prior to the initiation of this project, it was estimated that four European die casters were using the direct pressure sensor as part of their process monitoring techniques.

The primary objectives associated with usage of the direct pressure sensor is to accurately and repeatedly measure the liquid alloy pressure while in the die cavity and relate that pressure to the hydraulic pressure (and inferred liquid pressure) at the same time. If the gate completes freezing before the intensification pressure is applied, the pressure indicated by the in cavity direct pressure sensor should be the pressure value at the time of gate freezing, and not the metal pressure corresponding to the intensification pressure. It is not clear at this time if the increase in gas pressure in the cavity during filling will be measurable using this sensor.

Vent Flow Sensors

The amount of porosity (specifically gas porosity) in a die casting is also influenced by cavity venting. When the air initially present in the die cavity before the metal injection does not escape through the vents during the metal injection, the air is trapped in the casting as gas pores. Monitoring the condition of venting is important to control the total porosity of die castings.

Two types of devices were considered to monitor the condition of vents during a die casting operation. One was a microphone acoustic device and the other was a hot wire anemometer. The acoustic microphone sensor is primarily intended to monitor whether a vent is open or closed, rather than the instantaneous flow rate of gas exiting the vent. It is anticipated that an immediate need exists to implement a vent sensor which could indicate to the die casting operator whether or not the vent was functional (open) during the last shot. The need exists for a sensor which will indicate simply whether the vent is closed, 1/2 closed, or totally open.

The microphone acoustic pick up device consisted of five op-amps and two condenser microphones as shown in Figure 12. The microphones used to date are Radio Shack Replacement Condenser Microphone Element (Cat. No. 270-092B). One microphone was placed directly over a vent, and the other was placed near the first microphone, but off the vent. The op-amp # 3 in Figure 12 subtracts the signals detected by both microphones. This allows only signals generated from the vent to be sensed and eliminates other signals detected during a die casting operation. The op-amp # 5 controls output signals. It sends only signals which have more than a selected voltage to the output. The filtering voltage is controlled by the potentiometer. The output from this circuit was monitored by a Nicolet 4094. digital oscilloscope.

Figure 12. Circuit Diagram for Microphone Vent Sensors

The characteristics of the microphone acoustic pick-up device were investigated by using various signal sources. Hand claps and air flows created by a medical plunger were generated near one of the two microphones, and the output signals were displayed on the oscilloscope screen. A typical signal obtained from a hand clap is shown in Figure 13. The clap was recorded as a surge, which then gradually disappeared, and the intensity of the signal returned to the baseline. The gradual decay of the intensity was a circuit characteristic.

Figure 13: Acoustic Response to Hand Clap

Air flow through a vent during a die casting operation was simulated by ejecting air from a medical plunger with a 1 mm diameter orifice. A microphone was placed 20 mm above the exit of a 20 cc medical plunger, and 10 and 20 cc of ambient temperature air was ejected against the microphone by pushing the plunger by hand. A representative signal created by ejecting 20 cc of air is shown in Figure 14. Intensity gradually increased with respect to time, and reached the maximum value at the moment when the tip of the plunger hit the end wall of the medical plunger. Then the signal gradually returned to the baseline. The gradual decay of the intensity was considered a characteristic of this circuit. The duration of the air flow created by this system was determined at the location where the intensity began to decay. For the particular case shown in Figure 14, the duration of the air flow was about 43 ms. Figure 15 shows the signal obtained during a 10 cc air ejection. The duration of air flow for this case was about 12 ms. These time responses are anticipated to be similar to those associated with the vent exhaust.

Figure 14. Representative Acoustic Response to 20 cc Air Flow

Figure 15. Representative Acoustic Response to 10 cc Air Flow

An actual die casting operation involves many sources of acoustic signals. A large amplitude, short duration sound, like a clap, is anticipated at the completion of the filling. It is important to pick up only signals associated with venting to monitor the condition of the vents. However, most signals created by sounds are much weaker than the signals created by the direct flow of air against a microphone. For example, the highest intensity observed from a clap was about 50 mV, whereas the highest intensity observed by exposing a microphone in an air flow created by ejecting 20 cc air was about 3 V. The signal from a clap would not be detected during the air flow measurement because it is 60 times smaller than the signal commonly observed by the air flow. Although the second microphone was incorporated to subtract the background noises, it may not be necessary during the actual measurement of air flow from vents.

A hot wire anemometer consists of a heated platinum wire and precision resistance measurement equipment^[12]. The electrical resistance of platinum is known to change proportionally with temperature. At an initial stage, the platinum wire in an anemometer is kept under constant temperature by supplying a fixed electric voltage. When this platinum wire is exposed under steady fluid flow, the temperature of the wire changes correspondingly with the rate of the flow. This temperature variation appears in the change on the resistance. The resistance measurement equipment connected to the anemometer converts the resistance drop to the corresponding flow rate.

Several commercial anemometers were investigated for this study. The survey indicated that the response time of the commercially available anemometers was not adequate to measure venting time, which is typically 50 to 100 ms. The microphone acoustic pick-up device was selected for initial usage in this study because the response time of this device is more appropriate.

Part/Die Configuration

The selection of a die casting geometry and associated die is an important factor in evaluating the various sensors. The OSU ERC/NSM provided a die which could be modified and fit with the various sensors under evaluation and allows the die casting of a part which can be easily characterized. The part and associated die are identified as the wall die casting. A schematic illustration of the wall die casting is shown in Figure 16. Appropriate features of the wall die casting include:

- (1) the presence of a relatively flat, uniform thickness gate area, which is preferred for the location of opposing temperature probes for an accurate measurement of the gate freezing time,
- (2) the availability of flat, uniform thickness, regions in the casting for the measurement of both freezing time and pressure via the usage of both temperature and pressure sensors.
- (3) the convenient location of vents which allow the placement and usage of vent flow sensors.
- (4) the presence of walls which allow for assessing the effect of the process parameters on the quality of the casting in the blind (unvented) wall areas versus the ventable areas,
- (5) the die casting size and shape which allow for easy radiographic determination of porosity distribution and Archimedes' density measurements.

For the initial campaigns, four temperature probes (two on opposing sides of the gate, and two on opposing sides of the floor of the casting) and one pressure probe are to be used at the locations indicated in Figure 17. Venting measurements are initially limited to the establishment of whether venting occurs or not and the duration of gas exhaust from the die cavity.

Figure 16. Schematic Illustration of the Wall Die Casting

Figure 17. Illustration of Wall Die Casting Showing Location of Sensors

The die cast part selected for use in this project has been successfully cast at OSU as part of a previous study of dimensional variation as a function of die casting operating conditions^[13]. However, none of the near cavity sensors evaluated in this project were employed in that study.

Anticipated Sensor Outputs and Relation to Casting Quality

The output of each sensor is an e.m.f. that is collected using a computer based data acquisition system. The frequency of data collection is rather high as most of the die casting events, such as cavity filling, pressure intensification, and vent exhausting, occur in time frames of tens of milliseconds. Continuously collecting data at this rate throughout the entire casting cycle would generate a large data set which would require relatively large memory storage devices. A time regime has been established for each sensor during which data collection can be triggered and stopped during each casting cycle to limit the collected data to that essential for the process monitoring and next shot control. For example, if the total casting cycle is 30 seconds, the temperature sensors about the gate only need to be monitored for the several seconds until the part completes freezing or the 10 seconds during the die is closed. The pressure sensor data collection can be triggered from the plunger when the shot begins and will terminate several seconds later, when the casting cavity is completely filled and begins solidifying. Data from the vent flow sensor will only be collected for about 1 second during cavity filling.

Selected sensor response data (thermal probe data in the vicinity of the gates to determine gate freezing time) will require transfer and analysis at a later time (that is, do not allow real time analysis). The aluminum die castings made in the die casting campaigns in which the sensors are used will be characterized for gas content (using the vacuum fusion method) and total porosity (using the Archimedes' method). Predictions of the total porosity and contained gas contents will be made based on the sensor outputs prior to measuring the quality values. Values predicted using sensor data will then be compared to values experimentally determined from castings. Finally, an assessment of the viability of using in-cavity sensors to predict the porosity of castings on a shot-to-shot basis will be made.

Second Year Activities

Project activities during the second year of the project will be consistent with the previously defined project subtasks and project schedule. Work will continue to calibrate and evaluate near cavity sensors for use on the OSU die casting system. Delivery of the Buhler SC die casting machine is expected in mid-August, 1995. The first die casting campaign with all three types of sensors (thermal probes, direct cavity pressure sensors, and vent flow sensors) used with the wall casting is scheduled for completion by September 15, 1995. The quality measurements for the die castings made in that campaign should be completed by mid October, 1995.

Simultaneously, one or two aluminum alloy die casting companies will begin to use and evaluate the near cavity sensors identified to date on selected dies and parts in their commercial operations. One company has indicated their intention to install several of the near cavity sensors on a commercial part die and begin collecting sensor response data. The sensor data and parts made during process monitored campaigns will be shared with the OSU investigators for inclusion in this project. The OSU investigators on this project will work with the commercial die casting plant staff in evaluating the adequacy of the sensors and their ability to predict part quality.

Appendix A: NADCA Process Technology Task Group

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Appendix B: Project Review Meetings

<u>DATES</u>	<u>PLACE</u>	<u>ACTIVITIES</u>
8/25/94	NADCA, Rosemont, IL	Project Initiation Meeting with Process Technology Task Group
8/26/94	NADCA, Rosemont, IL	Project Review with NADCA R&D Committee
11/29/94	NADCA, Rosemont, IL	Review with Process Technology Task Group
11/30/94	NADCA, Rosemont, IL	Review with NADCA R&D Committee
1/10/95	PNGV, Auburn Hills, MI	Presentation to Big Three US Auto Manufactures
1/17/95	Heick Die Casting, Chicago, IL	Project review with G. Pribyl
1/17/95	Chicago NADCA Chapter	Presentation to NADCA Chapter
1/22/95	Cleveland, OH	NADCA Die Materials Committee Meeting and Review
3/1/95	Toledo AFS Chapter	Presentation to AFS Chapter
3/7/95	NADCA, Rosemont, IL	NADCA R&D Committee Meeting & Project Review
3/15/95	Chrysler, Auburn Hills, MI	PNGV Meeting
3/23/95	Wisconsin NADCA Chapter	Presentation to NADCA Chapter
6/14/95	NADCA, Rosemont, IL	Project Review with Process Technology Task Group & R&D Committees

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North American
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NADCA® SURVEY ON DIE CAVITY INSTRUMENTATION

1. a. How many cold chamber die casting machines are in your plant? _____
b. How many hot chamber die casting machines are in your plant? _____
2. a. How many cold chamber die casting machines is your plant currently operating? _____
b. How many hot chamber die casting machines is your plant currently operating? _____
3. Do you have the capability of measuring the plunger position and velocity and cylinder pressure as a function of time during a shot? ☐ Yes ☐ No
4. Do you record plunger position and velocity and cylinder pressure?
☐ Every shot ☐ Every _____ shots
☐ Only during setup or when there is a problem with the process
5. How many dies that you use are instrumented with thermocouples? _____
6. Do you record the die thermocouple response as a function of time during a shot?
☐ Every shot ☐ Every _____ shots
☐ Only when there is a problem with the die or process
7. During a die use campaign, do you record die coolant temperature?
☐ Continuously ☐ Intermittently ☐ Never
8. During a die use campaign, do you record die coolant flow rate?
☐ Continuously ☐ Intermittently ☐ Never
9. Have you or do you make temperature or pressure measurements in or near the die cavity as part of your process monitoring or control? ☐ Yes ☐ No
10. Do you utilize any instrument or measurement device to monitor the extent to which the die cavity vents are open or functioning? ☐ Yes ☐ No
11. Do you use any method or device to measure the amount of gas removed from the die cavity during filling?
☐ Yes ☐ No
12. What instrumentation devices have you used to make die cavity or near die cavity process measurements?
☐ Thermocouples ☐ Transducers
☐ Strain Gauges ☐ Other (Please explain): _____
13. Where or how did you obtain the die cavity instrumentation devices or units? For example, were they purchased as a complete unit from a commercial supplier or constructed from components by your engineering staff?

(over)

Appendix D (continued)

NADCA® SURVEY ON DIE CAVITY INSTRUMENTATION (continued)

14. If the die cavity instrumentation devices or units were obtained from a source outside your die casting facility, please give us the supplier's name and phone number or, whom at your company we can call for the information.

15. Were the die cavity instrumentation devices used to continuously monitor your process or as a means of solving a die design or part production problem?

16. What are the major capabilities and limitations of the die cavity instrumentation devices that you have used?

If you wish your company to remain anonymous, please skip questions 17 and 18.

17. As a member of NADCA, would you like to participate in the NADCA Process Technology Task Group die cavity instrumentation project? ☐ Yes ☐ No

☐ Please contact me about participation on the NADCA Process Technology Task Group.

18. Please provide the name of the individual completing this survey and your company's address, telephone and/or fax number:

Individual's Name: _____

Company Name: _____

Company Address: _____

Company Phone: _____

Company Fax: _____

Please return your completed survey to:

Attention: Professor Carroll Mobley
c/o Ohio State University
Dept. MSE
Fontana
116 West 19th Avenue
Columbus, Ohio 43210
Fax: (614) 292-1537

(10/20/94)

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Annual Report

on

Die Soldering Program

Submitted to

U.S. Department of Energy
Contract #DE-FC07-94ID13223

Annual Report Number 1
Report Date: July 31, 1995
Period Covered: July 1, 1994 - June 30, 1995

Report Prepared by
Frank Goodwin
Center for Die Casting

Two principal tasks were undertaken during the reporting period: a literature survey and preparatory die casting campaigns for the structured experiments that will be carried out during the second year of the program.

Regarding the literature survey, two primary sources of information were searched: published information from the open literature and technical information from the files of private organizations. All information was gathered by the end of April and included all information relating to the subject that had been carried out during the last 15 years. Several private organizations were generous in supplying data to the program. An overall survey has been synthesized and is being prepared in the form of a report. An oral report was given at the second meeting of the Industrial Monitoring Team held on May 4, 1995.

Four preliminary trials using the research die casting machine were carried out during this year. It was necessary to conduct these trials in order to locate the proper "window" of die casting process variables that will allow die soldering conditions to be reproducibly observed. It proved difficult to obtain die soldering conditions during the first two trials which relied upon a ramp in front of the ingate within the die cavity where it was expected die soldering would occur. Therefore, a solder pin was placed just in front of this ramp for the third trial and the gate redesigned by narrowing it to half of its original width while doubling its depth. Metal buildup on this solder pin was seen and an SEM analysis of the pin showed an aluminum-rich phase present in the built up area. During the fourth trial, the ramp used for the first three trials was replaced by a 90° (vertical) wall. This had 0° draft on the front and back. The solder pin was located directly in front of this wall. Soldered areas were found on both the pin and around the sides of the wall.

During discussion of the results of these trials at the IMT meeting, it became apparent that soldering in zinc die castings is related to growth of a deposition layer. This layer is distinct from a reaction layer because it is very low in iron content. It is apparent that erosion of the die surface is not linked to the phenomenon of soldering in zinc die castings. Thus, soldering in zinc die castings is very distinct from soldering in aluminum die castings where erosion always occurs and therefore soldering in zinc and aluminum die castings should be thought about and treated in very different ways.

Along with metallurgical analyses associated with the four preliminary trials, metallurgical analyses were also carried out on soldered core pins that had been contributed by members of the IMT. Agreeing with the preliminary laboratory trials, metal build up was seen in recessed areas especially areas within the industrial pins that had recessed flutes. A significant Al-Mg deposition layer was seen immediately adjacent to the steel surface. A very thin reaction layer containing iron (<1 micron) is found under this layer, contrasting with the situation in aluminum die castings where the reaction layer is significantly thicker. This was further evidenced that deposition, rather than reaction, is the operative mechanism during soldering of zinc die casting dies.

THE OHIO STATE UNIVERSITY

**JERRY BREVICK
CARROL MOBLEY**

DIE CASTING RESEARCH

Task 2 - Commercial Sensor Evaluation

Review of commercially available sensors is basically complete, however any new sensors that come on the market are also reviewed. The pressure sensors appropriate for this project have been identified, purchased, and received at OSU. Furthermore, the temperature and flow measurement instruments have been designed, constructed, and are being bench tested before mounting in the test die.

Task 3 - Sensor System Integration

During this period, work commenced on integrating the input signals from all of the sensors on a common time basis. A plan for accomplishing this has been developed and the capabilities of data acquisition systems to collect the data are being evaluated with respect to the requirements of the sensors.

Task 5 - Host Site Testing of Sensors

Recently, contacts were initiated with potential industrial host sites for the testing of sensors. At this time two possible sites are available. Visits to these sites have been scheduled for the next quarter.

**THE OHIO STATE UNIVERSITY
RAJIV SHIVPURI**

**EVALUATION OF CHROMIUM CARBIDE AND OTHER CVD
COATINGS TO IMPROVE THE WEAR RESISTANCE OF ALUMINUM
AND ZINC DIE CASTING DIES**

Following objectives have been accomplished during last quarter of research effort:

- i). Meeting with Industrial die casting partner: General Die Casters in Cleveland, Ohio. Several issues were discussed such as identification of multicavity die in the shop floor, the casting alloy 380, the process conditions and the key measurement of wear behavior of die materials and coatings.
- ii). Feasibility study of available potential commercial coatings in this project. A plant visit and cooperative discussion with the engineering group of Balzers Tool Coating Inc. was arranged on May 12. Several important coating issues were resolved: the die substrate hardness, the type of PVD and CVD coating to be tested, the die maintenance schedule, the frequency of off-line measurement, etc.
- iii). Establishment of GILD, Group for Increased Lives of Dies was accomplished with the support from industrial companies such as ALCOA, Balzers Tool Coating Inc., Multi-Arc, SAC International, General Die Casters, Ashland Chemicals. Cooperative agreement with each of our industrial team member is being initialized.
- iv). Accomplishment of a "State of Art" literature review was accomplished. The review paper "Application of Commercial Coating in Aluminum Die Casting" will be published in the International Conference on Advanced Technologies in Die/Mold Manufacturing to be held on October 10-12 in Columbus, Ohio.
- v). Completion of A Survey on Use of Die Coatings in Die Casting Industry. The survey was distributed through NADCA local chapters. The compilation of the review will be distributed to our NADCA members for their references. This review will benefit our selection of die coating in this project.

INTERNATIONAL LEAD ZINC RESEARCH ORGANIZATION, INC.

DIE SOLDERING PROGRAM

Work during this quarter of this project focused on defining the die soldering condition so that the primary variables for the designed factorial experiments could be accurately determined. This was done by continuing preliminary trials on the research die casting machine.

It has become apparent that die soldering in zinc die casting is significantly different from that seen with aluminum die casting. Soldering conditions with aluminum are normally seen as areas of direct impingement, whereas this research shows that metal buildup related to die soldering is located on areas where metal flow separation occurs. Approximately 350 shots are sufficient to produce such a buildup.

The experimental results were compared with a set of soldered core pins contributed by a die caster member of the industrial Monitoring Team. Consistent with the differences between aluminum and zinc die casting die soldering, a very thin reaction layer ($<1 \mu\text{m}$) was found under the built up zinc, whereas with aluminum this layer is significantly thicker.